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Nonlinear transient stability study of two lobe symmetric hole entry worn hybrid journal bearing operating with non-Newtonian lubricant

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ABSTRACT

The present paper, deals with a theoretical study concerning the effect of non-Newtonian lubricant on the stability of a two lobe symmetric hole entry worn hybrid journal bearing, compensated with constant flow valve restrictor. Trajectories of journal center motion have been obtained by solving the nonlinear equation of motion for the journal center with the Runge–Kutta method. The numerically simulated results indicate that the non-Newtonian behavior of the lubricant has a profound influence on the journal trajectories and stability of a worn hybrid journal bearing. A proper selection of parameters such as offset factor, wear depth parameter and the non-linearity factor may provide better bearing stability.

1. Introduction

The non circular hydrostatic/hybrid journal bearings have been extensively used in many high speed engineering applications such as turbo machinery, cryogenic and test equipments. The non circular journal bearing configurations have attracted a considerable attention of many researchers because of their improved bearing stability. In recent years, an enormous number of studies pertaining to non circular journal bearings, both analytical and experimental have been reported in literature [1–10]. During operation, these bearings normally run over a number of cycles and are subjected to frequent rotor rubs when the machine undergoes start-up and stop-down operations. During these transient periods, the bearing bush slowly wears out owing to abrasive action. As a result of this, the bearing geometry gets altered thereby changing its performance. Thus, it becomes imperative to consider the influence of wear in the analysis of this bearing. Many experimental and analytical studies pertaining to worn out journal bearings have been reported in the literature [8–18]. A study by Redcliff and Vohr [12] reported the first prevalence of wear in the circular hydrostatic journal bearing. Dufrane et al. [13] studied the wear mechanism in fluid film bearings owing to frequent start/stop operations. They reported that the wear damage will occur symmetrically every time on the bottom surface. The worn out bottom surface region of the bearing was first modeled and then experimentally validated by them. A number of studies have also been reported in the literature referring to Dufrane's model to investigate the influence of wear on the bearing performance [8–11,15–18].

In order to enhance the performance characteristics of lubricating oil, additives are often mixed with lubricant so as to fulfill the precise needs of various engineering applications. Several tribologists have claimed that the bearing performance could be improved by usage of high molecular weight polymers [19–23] as additives. The addition of these high molecular weight polymer additives causes industrial lubricants to behave as non-Newtonian fluids. The viscosities of these lubricants follow non-linear relationships between shear stress and shear strain rate [19–22].

The stability of rotating system is an integral facet within the analysis and design of the fluid film bearing systems. Rotor bearing system instability has gained significant importance and extensive investigations have been carried out to improve the stability of hydrodynamic journal bearing [24–38]. In 1925, based on experimental study, Newkirk and Taylor [24] reported a new kind of self-excited rotor dynamic instability in hydrodynamic journal bearings. They observed that the instability occurred, due to the action of oil film and christened this self-excited rotor dynamic instability as oil whirl. Pinkus [25], through experiments investigated the influence of load, viscosity, flexibility, unbalance and external excitation on oil whirl and reported that the stability of the rotor bearing system depends on low lubricant temperature. Choy et al. [27] and Braun et al. [28] studied the non-linear characteristics and their effects on the transient response of a plain journal bearing. Further, they compared the linear and non-linear bearing characteristics for various operating conditions of bearing. Malik et al. [29] carried out a theoretical study dealing with the transient response of a

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Nomenclature

a_b	bearing land width, mm
c	radial clearance, mm
e	journal eccentricity, mm
E	Young's modulus of elasticity, N mm^{-2}
F	fluid film reaction $(\partial h/\partial t \neq 0)$, N
F_x, F_z	components of fluid film reactions in X and Z direction $(\partial h/\partial t \neq 0)$, N
F_o	fluid film reaction $(\partial h/\partial t = 0)$, N
C_1	clearance due to circumscribed circle on the bearing, mm
C_2	clearance due to inscribed circle on the bearing, mm
g	acceleration due to gravity, m s^{-2}
h	nominal fluid-film thickness, mm
$h_{\min}$	minimum fluid film thickness, mm
L	bearing length, mm
R_J, R_L, R_b	radius of journal, lobe and bearing, mm
p	pressure, N mm^{-2}
Q	bearing flow, mm^3 s^{-1}
S_{ij}	stiffness coefficients $(i, j = X, Z)$, N mm^{-1}
C_{ij}	damping coefficients $(i, j = X, Z)$, N s mm^{-1}
t	time, s
δ_W	wear depth, mm
n	number of rows of holes
K	nonlinearity factor for cubic shear law
τ	shear stress in lubricant film, N mm^{-2}
$\dot{\gamma}$	shear strain rate, s^{-1}
μ_a	apparent viscosity, N s m^{-2}
ω_I	$(g/c)^{1/2}$, rad s^{-1}
D	journal diameter, mm
W_o	external load, N
X, Y, Z	Cartesian coordinates
X_J, Z_J	coordinates of steady state equilibrium journal center from geometric center of bearing, mm

Greek symbols

$\lambda = L/D$,	aspect ratio
ϕ	attitude angle
μ	dynamic viscosity of lubricant, N s m^{-2}
μ_r	dynamic viscosity of lubricant at reference inlet temperature and ambient pressure, N s m^{-2}
ρ	density of the lubricant kg mm^{-3}
O_j, O_{Li}	journal centre, lobe centre
ω_J	journal rotational speed, rad s^{-1}
ω_{th}	threshold speed, rad s^{-1}
p_s	lubricant supply pressure N mm^{-2}

Non-dimensional parameters

$\bar{a}_b = a_b/L$,	land width ratio
$\beta^* = p^*/p_s$,	concentric design pressure ratio
$\overline{Q}_R =$	$\overline{Q}_C$,
$\overline{Q}_C =$	$Q(\mu_r/C^3 p_s)$
$\overline{C}_{ij} =$	$C_{ij}(c^3/\mu R_J^4)$
$(\overline{F}, \overline{F}_o) =$	$(F, F_o)/p_s R_J^2$
$(\bar{h}) =$	$(h)/c$
$\bar{\delta}_W =$	δ_W/c
$\bar{p}, \bar{p}_c, \bar{p}_{\max} =$	$(p, p_c, p_{\max})/p_s$
$\overline{Q} =$	$Q(\mu/c^3 p_s)$
$\overline{S}_{ij} =$	$S_{ij}(c/p_s R_J^2)$
$\overline{W}_o =$	$W_o/p_s R_J^2$;
$(\overline{X}_J, \overline{Z}_J) =$	$(X_J, Z_J)/c$
$\bar{t} =$	$t(c^2 p_s/\mu R_J^2)$
$\overline{X}^i{}_L, \overline{Z}^i{}_L =$	$(X^i{}_L, Z^i{}_L)/c$
$\alpha, \beta = (X, Y)/R_J$,	circumferential and axial coordinates;
$\varepsilon =$	e/c, eccentricity ratio
$\alpha_b, \alpha_e =$	start and end of the worn region
$\delta =$	C_1/C_2, offset factor
$\bar{\delta}_W =$	δ_W/c
$\bar{\mu} =$	μ/μ_r
$\bar{\tau} =$	$(\tau/(cp_s/R_J))$
$\bar{\dot{\gamma}} =$	$(\dot{\gamma}/(cp_s/\mu_r R_J))$
$\overline{K} =$	$(cp_s/R_J)^2 K$
$\bar{\omega}_{th} =$	ω_{th}/ω_I
$\Omega =$	$\omega_J(\mu R_J^2/c^2 p_s)$, speed parameter

Matrices

$N_i, N_j =$	shape functions
$[\overline{F}]$	assembled fluidity matrix
$\{\bar{p}\}$	nodal pressure vector
$\{\overline{Q}\}$	nodal flow vector
$\{\overline{R}_H\}$	column vectors due to hydrodynamic terms
$\{\overline{R}_{Xj}\}, \{\overline{R}_{Zj}\}$	global right hand side vector due to journal center velocities.

Subscripts and superscripts

b :	bearing
J :	journal
R :	restrictor
s :	supply
l:	lobe
i:	lobe number
min:	minimum
max:	maximum
x, y, z :	components in X, Y, and Z directions
.:	first derivative w.r.t. time
r:	reference value
*:	concentric operation
..:	second derivative w.r.t. time
–:	non dimensional parameter

journal in short bearings during acceleration and deceleration periods. Chandrawat and Sinhasan [30] and Jain et al. [31] studied the effect of bearing shell flexibility on transient response of a hydrodynamic journal bearing system. They reported that the motion trajectory obtained by nonlinear analysis provides a much higher stability margin in terms of critical mass, than those obtained through linearized analysis. Raghunandana et al. [32] and Sinhasan and Goyal [33], carried out the study, for rigid hydrodynamic circular and two-lobe journal bearings operating with non-Newtonian lubricant respectively, they showed that the non-linear analysis predicts a lower critical journal mass parameter than that predicted by linear analysis. Both studies [32,33] indicate a considerable reduction in the stability of journal bearing system operating with non-Newtonian lubricant as compared to the bearing lubricated with Newtonian lubricant. The influence of 3D surface roughness of the transient non-Newtonian response of a dynamically loaded journal bearing under